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14. ABSTRACT
This project has experimentally characterized the coherent quantum nature of the superconducting persistent current qubits which were fabricated in the trilayer niobium technology. The quantum levels of these qubits have been mapped out using both standard microwave frequency spectroscopy as well as a new technique of amplitude spectroscopy. Important to the future implementation of these qubits for quantum computing applications is the demonstration of microwave sideband cooling of the qubits as well as a resonant read-out scheme. In addition to characterizing the quantum nature of a single qubit, this work has also explored the use of Rapid-Single-Flux superconducting circuits to rapidly control the qubit system.

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Final Report for the Air Force Office of Scientific Research, Grant F49620-01-1-0457
Quantum Computation with Superconducting Quantum Devices

June 1, 2001 – September 30, 2007

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I. Abstract:

This project has experimentally characterized the coherent quantum nature of the superconducting persistent current qubits which were fabricated in the trilayer niobium technology. The quantum levels of these qubits have been mapped out using both standard microwave frequency spectroscopy as well as a new technique of amplitude spectroscopy. Important to the future implementation of these qubits for quantum computing applications is the demonstration of microwave sideband cooling of the qubits as well as a resonant read-out scheme. In addition to characterizing the quantum nature of a single qubit, this work has also explored the use of Rapid-Single-Flux superconducting circuits to rapidly control the qubit system.

II. Main Project Goals:

We have used superconducting circuits with Josephson junctions (1) to implement the fabrication and demonstrate coherent control of superconducting qubits, and (2) to model the measurement process, understand decoherence, and develop scalable control methods and algorithms, and (3) to **c**ombine these superconducting qubits with classical cryogenic control electronics.

III. Project Description:

Here we use superconducting circuits as components for quantum computing.. Quantum computation holds the potential to solve problems currently intractable with today's computers. Information in a quantum computer is stored on quantum variables, and that information is processed by making those variables interact in a way that preserves quantum coherence. Typically, these variables consist of two quantum states, and the quantum device is called a quantum bit or qubit. Superconducting quantum circuits have been proposed as qubits, in which circulating currents of opposite polarity characterize the two quantum states. The goal of the present research is to use superconducting quantum circuits to realize a fully functional qubit, to perform measurement of these qubits, to model the sources of decoherence, and to develop scalable algorithms. A particularly promising feature of using superconducting technology is the potential of developing high-speed, on-chip control circuitry with classical, high-speed superconducting electronics. The picosecond time scales of this electronics means that the superconducting qubits can be controlled rapidly enough that the qubits remain phase-coherent over the lifetime of the computation.

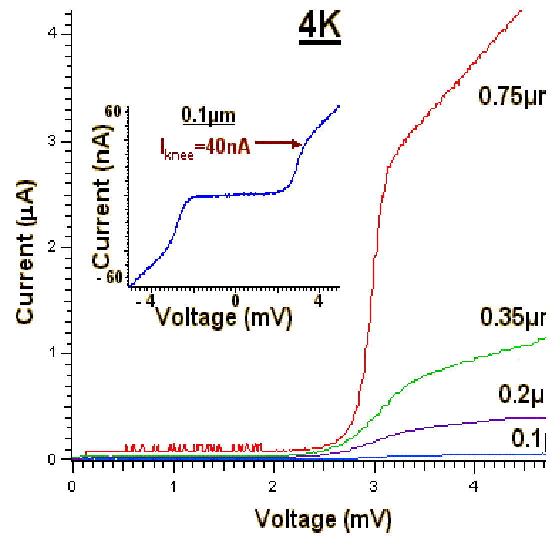
Summary of Main Results:

1. Niobium Superconducting Persistent-Current Qubits with Deep Submicron Josephson Junctions (MIT)

The basic component of a quantum computer is the qubit, the quantum analog to today's bits. Any two-level quantum system could serve as a qubit; however, the qubit must satisfy two major criteria for practical quantum computing: long coherence times and the ability to scale to thousands of qubits. Persistent-current (PC) qubits are promising candidates for realizing such a large-scale quantum computer. The PC qubit is a superconducting circuit with Josephson Junction elements, which can be effectively operated as a two-level quantum system [1].

With a tri-layer process using optical lithography, we can create the deep-submicron Josephson Junctions required to realize large qubit tunnel-couplings, which allow improved immunity to dielectric-induced decoherence, and there is no foreseeable barrier to large-scale integration. We have recently begun measuring and characterizing the PC qubits designed with these deep-submicron Josephson Junctions fabricated with the Nb-Al/AlOx-Nb trilayers. Initial testing of the Josephson Junctions shows excellent

performance down to sizes necessary for long decoherence times (Figure 1), and first studies of how the ground state of the new qubits changes as you sweep the applied DC flux show the large tunnel-couplings we were aiming for (Figure 2).



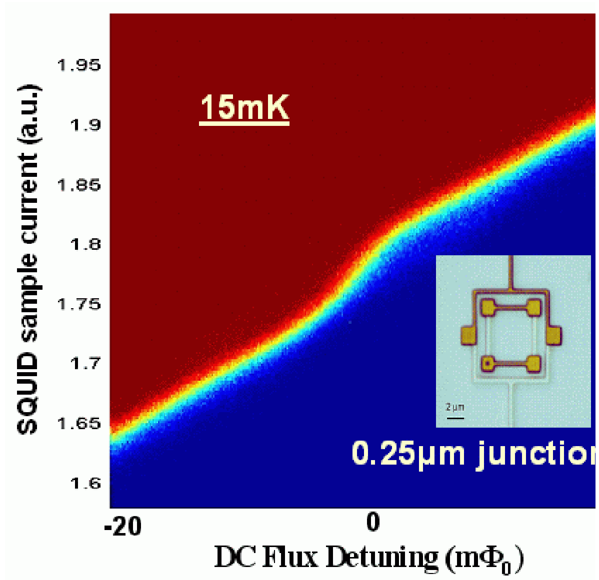


Figure 1 : IV traces taken at 4K for a few different test junctions, from 0.75 µm down to 0.1µm. Blown up in the inset is the 0.1 µm junction IV and we see a knee current of 40nA and a very large subgap resistance.

Figure 2 : Qubit step taken at dilution refrigerator temperatures with the device seen in the inset, where the larger junctions are 250nm on a side . One can clearly see that as you change the applied dc magnetic flux one sees the transition of the ground state from one circulating current state to the other.

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2. Mach-Zehnder Interferometry in a Persistent-Current Qubit (MIT)

We have demonstrated Mach-Zehnder (MZ)-type interferometry with a niobium superconducting persistent-current qubit. These experiments exhibit remarkable agreement with theory, and they will find application to non-adiabatic qubit control methods. The qubit is an artificial atom, the ground and first-excited states of which exhibit an avoided crossing. Driving the qubit with a large-amplitude harmonic excitation sweeps it through this avoided crossing two times per period. The induced Landau-Zener (LZ) transitions at the avoided crossing cause coherent population transfer between the eigenstates, and the accumulated phase between LZ transitions varies with the driving amplitude. This is analogous to a Mach-Zehnder interferometer, where the LZ transition is the beasmplitter and the relative phase accumulated between LZ transitions is the optical path length difference between the arms of the interferometer. Over the entire length of the microwave driving pulse we have a sequence of Mach-

Zehnder interferometers. We have observed MZ quantum interference fringes as a function of the driving amplitude for single- and multi-photon excitations.

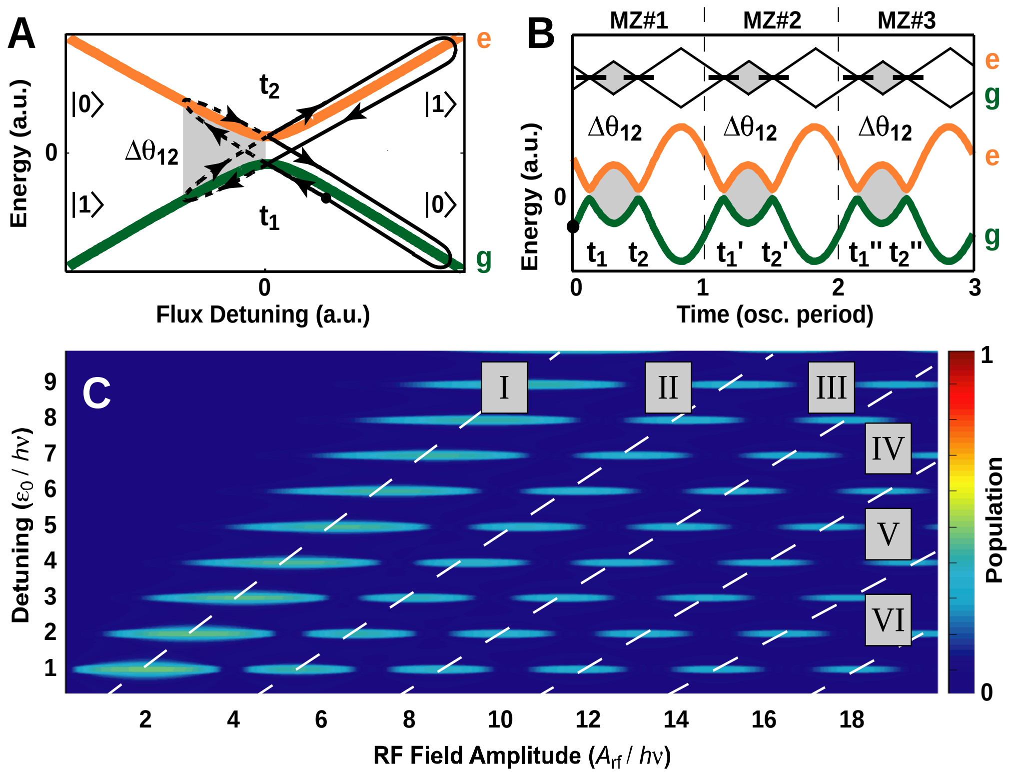

Figure 1: (a) Energy of the two-level system. Starting at the marker, the qubit state is swept through the avoided crossing twice, accumulating a phase between the LZ transitions that occur. (b) The corresponding energy variation over a few pulse periods. The sequence of LZ transitions and phase accumulation are analogous to a sequence of Mach-Zehnder interferometers. (c) Qubit population as a function of driving amplitude. We see the Bessel dependence to the Mach-Zehnder-like quantum interference for n-photon transitions.

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[1] W.D. Oliver, Y. Yu, J.C. Lee, K.K. Berggren, L.S. Levitov, T.P. Orlando, "Mach-Zehnder Interferometry in a Strong Driven Superconducting Qubit," *Science* 310(9): 1653-1657 (December 2005)

3. Coherent Quasi-classical Dynamics of a Niobium Persistent-Current Qubit (MIT)

We have recently demonstrated Mach-Zehnder (MZ)-type interferometry in the persistent-current (PC) qubit, in the strong driving limit [1]. We have now extended this work to much lower driving frequencies. By driving our system at frequencies smaller than our linewidth we have observed a new regime of quasi-classical dynamics within the strong driving limit. Now a transition at a DC flux detuning resonant with n photons is assisted by neighboring resonances. In this regime we find remarkable agreement to

theory by assuming the population transfer rate for the nth photon resonance is the sum of rates from all other resonances.

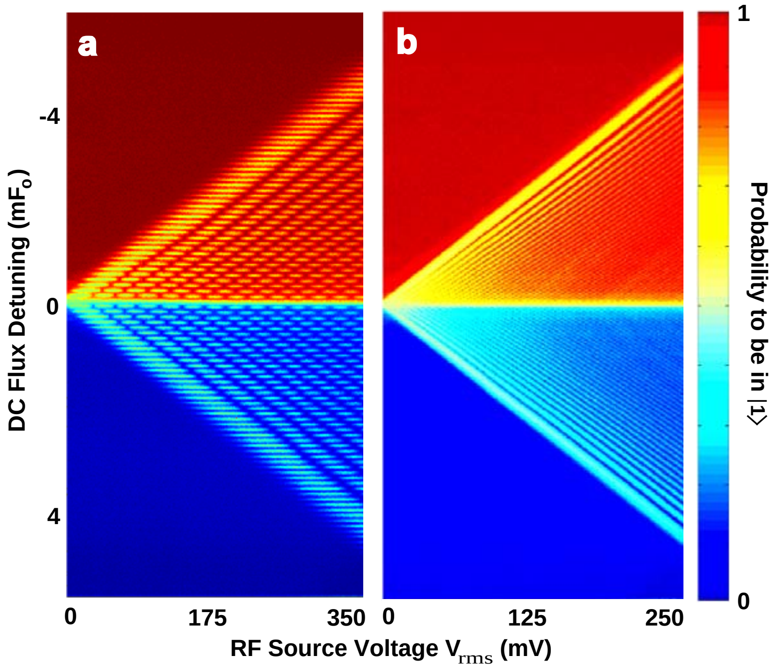

Figure 1: Qubit population as a function of driving amplitude. (a) Driving frequency = 270MHz. We see the Bessel dependence to the Mach-Zehnder-like quantum interference for n-photon transitions. (b) Driving frequency = 90MHz. Individual resonances are no longer distinguishable but we still see coherent quantum interference.

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4. Microwave-Induced Cooling of a Superconducting Qubit

We have recently demonstrated microwave-induced cooling in a superconducting flux qubit [1]. The thermal population in the first-excited state of the qubit is driven to a higher-excited state by way of a sideband transition. Subsequent relaxation into the ground state results in cooling. Effective temperatures as low as 3 millikelvin are achieved for bath temperatures from 30 - 400 millikelvin, a cooling factor between 10 and 100. This demonstration provides an analog to optical cooling of trapped ions and atoms and is generalizable to other solid-state quantum systems. Active cooling of qubits, applied to quantum information science, provides a means for qubit-state preparation with improved fidelity and for suppressing decoherence in multi-qubit systems.

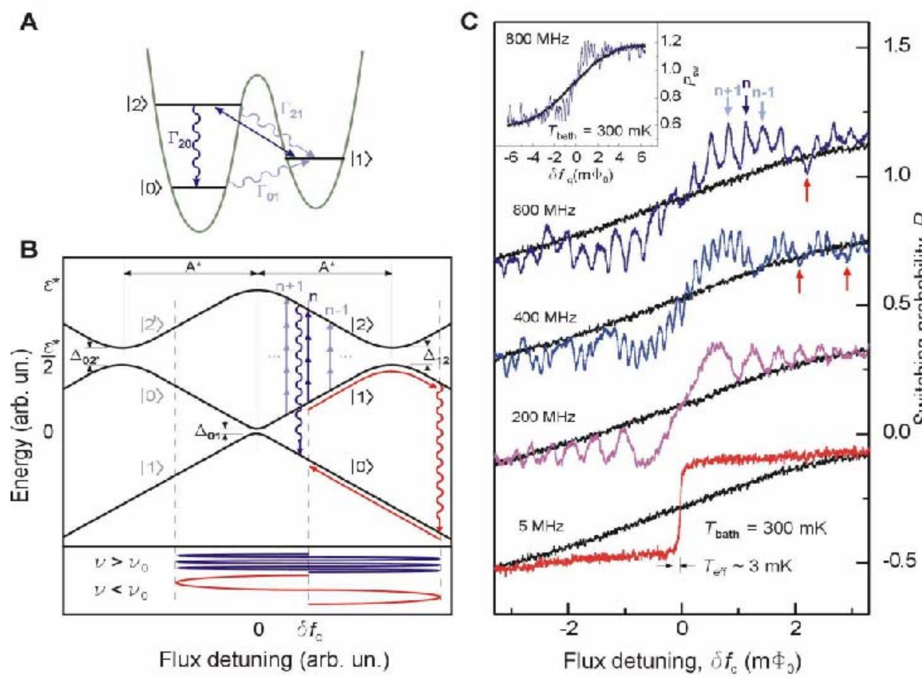

Figure 1: Sideband cooling in a flux qubit. (a) Double well illustration of cooling. External excitation transfers thermal population from state 1 to state 2, from which it decays to the ground state 0. (b) Band diagram illustion of cooling. 1 to 2 transitions are driven resonantly at high driving frequencies and occurr adiabatically at low driving frequency. (c) Thermal population cooled at different frequencies. Cooling from 300mK to as low as 3mK is shown.

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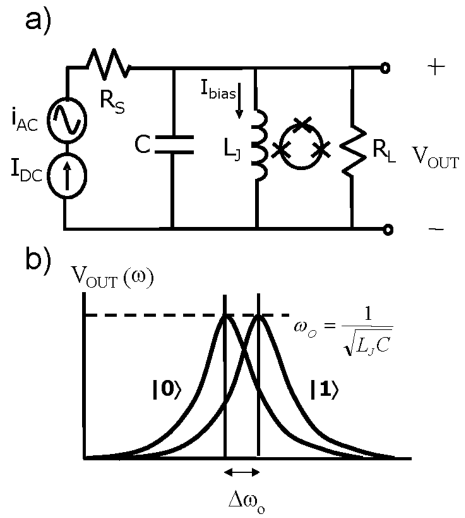
5. Resonant Readout of a Persistent Current Qubit (MIT)

The two logical states of a persistent current (PC) qubit correspond to oppositely circulating currents in the qubit loop. The induced magnetic flux associated with the current either adds to or subtracts from the background flux. The state of the qubit can thus be detected by a DC SQUID magnetometer inductively coupled to the qubit.

We have implemented a resonant technique that uses a SQUID as a flux-sensitive Josephson inductor for qubit readout. This approach keeps the readout SQUID biased at low currents along the supercurrent branch. The low bias reduces the level of decoherence on the qubit, and is more desirable for quantum computing applications. We incorporated the SQUID inductor in a high-Q on-chip resonant circuit, and were able to distinguish the two flux states of a niobium PC qubit by observing a shift in the resonant frequency of the readout circuit. The nonlinear nature of the SQUID Josephson

inductance as well as its effect on the resonant spectra of the readout circuit was also characterized.



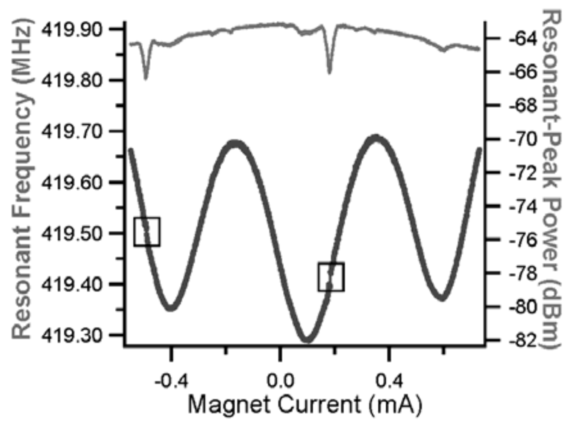


Figure 1a: The SQUID inductor is incorporated in a resonant readout circuit. It is inductively coupled to a PC qubit to detect its state. Figure 1b: A transition of the qubit state changes the Josephson inductance of the SQUID, and can be sensed as a shift in the resonant frequency of the readout circuit.

Figure 2: Experimental results at 300mK: the lower plot (left axis) shows the modulation of the resonant frequency with external magnetic field. Qubit steps corresponding to transitions between opposite flux states were observed at every 1.3 periods of the SQUID lobe. The upper plot (right axis) shows the corresponding peak amplitude of the resonant spectrum. The dip in peak power coincides with the qubit step.

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6. Large Amplitude Spectroscopy of the Persistent Current Qubit (MIT)

When a superconducting persistent current qubit is driven strong enough by the microwave radiation, higher energy levels and avoided crossings are accessed. This results in a new form of spectroscopy, which we have called “amplitude spectroscopy.” The technique can be used to completely characterize the full energy spectrum of the persistent current qubit, just by studying the qubit population as a function of driving amplitude and duration of the driving amplitude. The figure below demonstrates the spectroscopy diamonds that result from such measurements. (See Ph.D. Thesis of D. M. Berns, MIT 2008.)

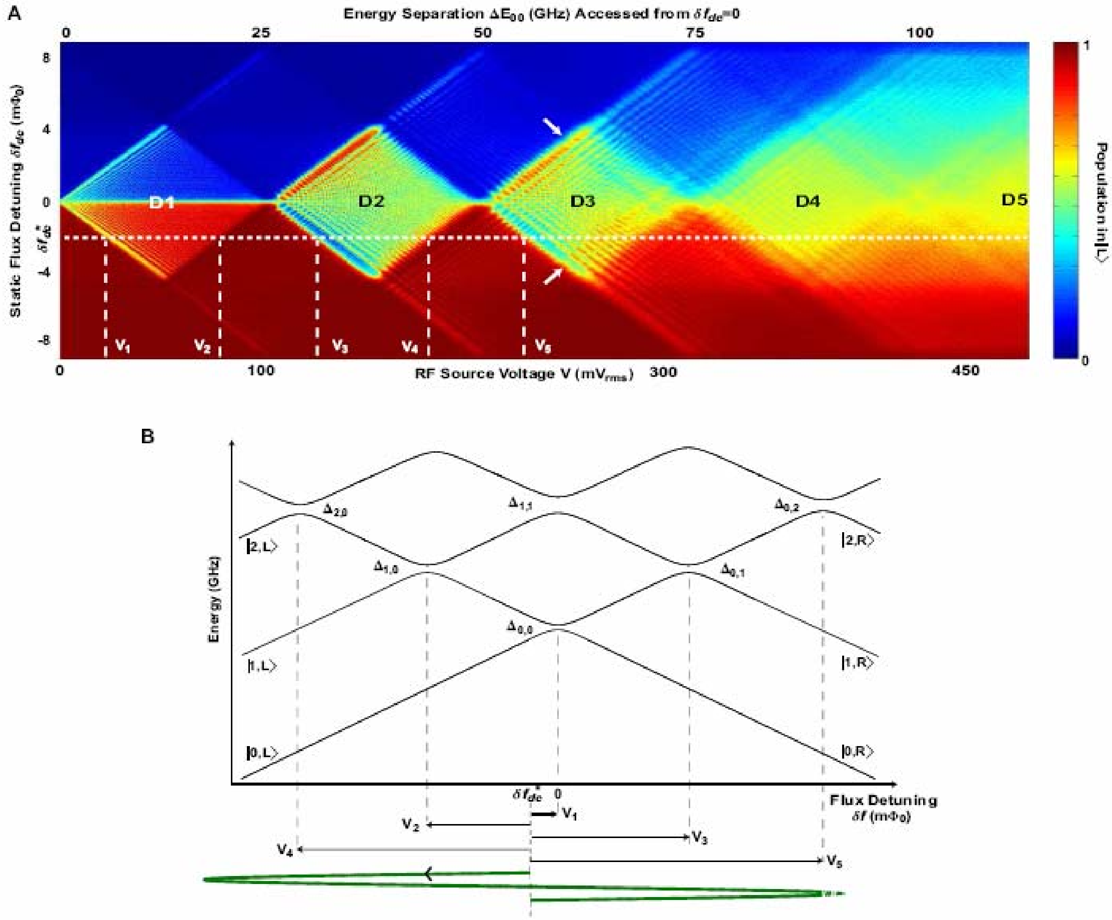

Figure 5-1: (**A**) Amplitude spectroscopy with long-pulse driving towards saturation. The qubit is driven at a fixed frequency $\nu = 0.160$ GHz, while amplitude V is swept for each static flux detuning δf_{dc}. The diamond edges signify the driving amplitude V for each value of δf_{dc} when an avoided level crossing is first reached (amplitudes $V_1 - V_5$ for $\delta f_{\mathrm{dc}} = \delta f^*_{\mathrm{dc}}$). The main diamond regions, symmetric about $\delta f_{\mathrm{dc}} = 0$, are labeled D1 to D5. Arrows indicate signatures of transverse mode coupling (see Fig. 5-9). Top axis: the $|0,\mathrm{L}\rangle - |0,\mathrm{R}\rangle$ energy spacing $\Delta E_{0,0}$ accessed by V from $\delta f_{\mathrm{dc}} = 0$. (**B**) Schematic energy-level diagram illustrating the relation between the driving amplitude V and the avoided crossing positions for a particular static flux detuning $\delta f_{\mathrm{dc}} = \delta f^*_{\mathrm{dc}}$. The arrows represent the amplitudes $V_1 - V_5$ of the RF field at which the illustrated avoided crossings are reached, marking the onset of the diamond regions in (A).

7. Thermometry using thermal activation of Josephson junctions at MilliKelvin temperatures. (Rochester)

We use the thermal activation of Josephson junctions as a thermometer to investigate heat flow from a hot resistor at milliKelvin temperatures on a silicon chip used for superconducting qubit experiments. The experiments are compared to computer simulations and agree well. These results indicate that on-chip resistors can be used below a certain power level, but not above that level.

8. Dressed States of Josephson phase qubit coupled to an LC circuit (Rochester)

We study the dynamics of a current biased Josephson phase qubit capacitively coupled to an LC circuit. We find that the eigenstates of this system are dressed states that are entangled states between the phase qubit and the LC resonator. We demonstrate that these dressed states can be probed by measuring the avoided crossing in the spectrum of the system. We present our experimental setup to investigate them. This system is interesting not only in demonstrating entanglement, the essential element for quantum information processing (QIP), but also in serving as a first step toward a solid-state analog of cavity QED.

9. Picosecond on-chip qubit control circuitry (Rochester)

Fast on-chip control of superconducting qubits has engaged complex and power consuming RSFQ circuits that currently pose more of an experimental burden than an asset. Measurements of quantum coherent oscillations of qubits require dilution refrigerator temperatures. The motivation of this design is to minimize the necessary bias leads and power dissipation for an SFQ based control circuit. Elimination of redundant circuit elements by innovative use of fundamental elements allows small-scale control circuitry.

IV. Personnel Supported

The following were supported in part by this contract:

MIT: Seth Lloyd (PI), Leonya Levitov (PI), Terry Orlando (PI), Johan Mooij (PI), Sergio Valenzuela (Research Scientist), Yang Yu (Postdoc), Jonathan Habif (Postdoc); and Graduate students: David M. Berns, Bryan Cord Donald Crankshaw, Janice Lee, Daniel Nakada, and Bhuwan Singh.

University of Rochester: Marc Feldman (PI), Mark Bocko (PI), postdoc Xingxiang Zhou Graduate students Jon Habif, Pavel Rott, and Michael Wulf,

Harvard: Michael Tinkham (PI) and Sergio Vanlenzula (Postdoc).

V. List of Journal Publications

1. D. M. Berns, W. D. Oliver, S. O. Valenzuela, A. V. Shytov, K. K. Berggren, L. S. Levitov, and T. P. Orlando, "*Amplitude Spectroscopy of a Supronducting Qubi*t," submitted for publication.

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VI. List of Theses:

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2. Pavel V. Rott, *Application of Superconducting Digital Electronics in Quantum Mechanical Experiments*, Ph.D. Thesis, University of Rochester, 2003.
3. Jonathan L. Habif, Effects of the Integration of Digital and Quantum Coherent Superconducting Electronics, Ph.D. Thesis, University of Rochester, 2003.
4. D.S. Crankshaw, *Measurement and On-chip Control of a Niobium Persistent Current Qubit*, Ph.D. Thesis, MIT, 2003.
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8. Janice. C. Lee, *Resonant Readout of a Superconducting Persistent Current Qubit*, Ph.D Thesis, MIT, 2006.
9. David Marc Berns, *Large Amplitude Driving of a Persistent Current Qubit*, Ph.D Thesis, MIT, 2008.